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NASA
Technical Memorandum 103278

AVSCOM
Technical Report 90-C-021

An Update of Engine System Research at the Army Propulsion Directorate

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Prepared for the
Rotary Wing Propulsion Specialists' Meeting
sponsored by the American Helicopter Society, Inc.
Williamsburg, Virginia, November 13-15, 1990

NASA

US ARMY
AVIATION
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SUMMARY

The Small Turboshaft Engine Research (STER) program is being conducted by the Army Propulsion Directorate at the NASA Lewis Research Center. This program provides a vehicle for evaluating the application of emerging technologies to Army turboshaft engine systems and to investigate system related phenomena. Capitalizing on the resources at hand, in the form of both the NASA facilities and the Army personnel, the program goal of developing a physical understanding of engine system dynamics and/or system interactions is being realized.

STER entries investigate concepts and components developed both in-house and out-of-house. Emphasis is placed upon evaluations which have evolved from on-going basic research (6.1) and advanced development (6.2) programs. Army aviation program managers are also encouraged to make use of STER resources, both people and facilities. The STER personnel have established their reputations as experts in the fields of engine system experimental evaluations and engine system related phenomena. The STER facility has demonstrated its utility in both research and development programs.

The STER program provides the Army aviation community the opportunity to perform system level investigations, and then to offer the findings to the entire engine community for their consideration in next generation propulsion systems. In this way results of the fundamental research being conducted to meet small turboshaft engine technology challenges expeditiously find their way into that next generation of propulsion systems.

INTRODUCTION

The success of a rotorcraft platform is tremendously sensitive to the performance of its propulsion system. The empty weight fraction made up by the propulsion system is higher for rotorcraft than for normal fixed wing aircraft. High specific power engines are a necessity. This is due, in part, to the fact that the rotorcraft must lift its own weight in hover, without the aid of lift induced by forward velocity; dual engine rotorcraft must also be able to land with one engine inoperative. The engine must produce adequate power and have rapid transient response at all envelope conditions to maintain nearly constant rotor speed regardless of the maneuver, load transient, or wind gust. Yet fuel control gains cannot be so high as to induce coupled engine, drive train, rotor and airframe instabilities, which in the worst case can be destructive. In addition, rotorcraft must be able to operate in terribly

harsh environments; the engines, at times, ingest air from dense clouds of recirculated hot exhaust gases and sand.

Given the importance of the propulsion system to a rotorcraft, the constraints and compromises to which it must be designed, and the environment in which it must perform, it must also be recognized that the gas turbines which provide the power for most rotorcraft have unique problems because they are small. Increasing reliability and durability in a high specific power package requires higher temperature materials. Cooling technologies usable in larger engines cannot be scaled to the smaller engines because of the incompatibility of component sizes and manufacturing technology. This makes new cooling techniques and materials which need little or no cooling a necessity. Likewise, the volumes of research done in the area of engine sensitivity to inlet distortion has emphasized large engines incorporating axial compressors. The applicability of that work to small gas turbines with high speed centrifugal and mixed axial-centrifugal compressors is limited.

The overall mission of the U.S. Army Propulsion Directorate (PRPD), co-located at the NASA Lewis Research Center, is to plan, develop, manage, and execute a portion of the Army Aviation System Command's (AVSCOM) program of research and exploratory development, with emphasis on rotorcraft propulsion and drive trains. The rotorcraft propulsion element of our mission brings attention to the special problems encountered with small turbomachines. Essentially all component and system technology areas are covered. Tasks involve both in-house research and contracted programs. These tasks are undertaken to stay ahead of the perceived requirements for future engine and drive train systems. Many projects are approached through joint programs with our NASA hosts.

This article highlights one of the Army Propulsion Directorate's major thrusts, the Small Turboshaft Engine Research (STER) program. The STER programs are experimental investigations into the physics of a complete, small turboshaft engine system involving component interactions and/or system dynamics. The evolution of the STER program since its establishment in 1978 is presented.

PROGRAM RATIONALE

The objective of the STER program is to evaluate advanced concepts in complete turboshaft engine systems. STER programs are not aimed at solving a development problem on an engine. Rather, each program is undertaken because there is a limited understanding of the engine's behavior at the system level. An investigation may involve the installation of an advanced technology component or system to assess its effect on engine performance, or it may involve the acquisition and analysis of data obtained while perturbing the engine from normal operation. Such studies lead to an understanding of the physics of the system related phenomena with a consequent reduction of the technical risk and cost in the engine research and development process. Their conduct in a government facility provides all of industry with access to results and findings, not restricted with proprietary labels, through consulting and reports in the open literature.

SMALL TURBINE ENGINE FACILITY

The STER facility is located in the NASA Lewis Research Center's Engine Components Research Laboratory. ECRL is an indoor, sea level engine test facility (fig. 1). An eddy current dynamometer, control system, gearbox and variable inertia provide a flexible, stable, fast response engine loading system. The building is equipped with a JP fuel system, shop air, gaseous nitrogen, city and cooling tower water, and combustible gases (gaseous hydrogen and natural gas). The rig has an atmospheric inlet and may use either atmospheric or altitude exhaust. A high pressure (450 psi) service air system is also available. Facility capabilities are summarized in figure 2.

Test programs are directed and observed from a control room located above and to the front of the installation. Data are monitored and acquired from this location. Steady state data are recorded on a distributed digital data acquisition system (ref. 1) making use of an Electronically Scanned Pressure measurement system (ref. 2) standard thermocouples, flow meters, speed and vibration pickups, and similar types of instrumentation found in most gas turbine test rigs. Other types of special instrumentation have been used as needed. Transient data is recorded on local tape recorders, visicorders, x-y plotters and on the NASA Lewis central analog system. ECRL now also has access to a new high speed digital data system which is being installed at Lewis.

STER PROGRAM HIGHLIGHTS

The first STER program was an investigation into the effect of an infrared suppressor on the performance of a T63 turboshaft engine (ref. 3). There had been concern that a suppressor designed for the T63-A-700 on the OH-58 helicopter was adversely affecting engine performance. Data were recorded with the standard exhaust stacks, and then with the IR suppressors installed (fig. 3). Analysis of the data showed that the IR suppressors had no measurable effect on performance.

Following that evaluation, the dynamics and distortion sensitivity of a turboshaft engine was investigated. A modified YT700 engine became our workhorse since it was the most modern technology small turboshaft available from within the Army inventory at that time. The program involved mapping the performance of the engine, both on and off the normal operating line (fig. 4). Inflow bleeding at the compressor exit was used to move off the operating line toward the surge line. The engine was then subjected to steady state inlet pressure and temperature distortions and to transient thermal distortions to document their effects on the engine performance. Various combinations of distortion intensity and extent were tested. The effect of thermal distortion ramp rate on engine stability was also documented (fig. 5). These efforts, reported in references 4 and 5, were used to improve design and off-design engine performance models used by both industry and the government. A further result of this program was the interest expressed by industry in the test hardware and the methods used to generate inlet temperature distortions. This led to our direct support of AVSCOM in the T800 inlet distortion sensitivity investigations.

The engine performance models produced in the dynamics and distortion program were used directly in the design of an advanced turboshaft control, the

next STER entry. The objective of the program was to evaluate the application of modern control theory on a turboshaft engine in order to improve power turbine governing while maintaining system stability. In the past, engine transient response has been compromised in order to maintain system stability. A power turbine governor, based on Linear Quadratic Regulator (LQR) theory, was designed and programmed into a microprocessor, and a T700 hydromechanical control unit (HMU) was modified to accept commands from the microprocessor (refs. 6 to 8). The electronic fuel control test bed was demonstrated by implementing the bill of material (BOM) control laws on the microprocessor and controlling the engine through the modified HMU. The digital BOM control duplicated engine performance with a hydromechanical control.

The microprocessor based digital control also provided the capability to perform tests which were used to improve models of the engine's sensitivity to variations in fuel flow and variable geometry. While introducing voltage perturbations into either the fuel flow or variable geometry command signal, the engine response was measured. The results of these model identification tests were used to finalize the engine model used in the LQR control design. An advance in test techniques was the use of pseudo random binary noise (PRBN) (refs. 8 and 9) in the model identification testing as the input perturbation. The LQR governor was analytically shown to improve engine response in many instances (table I). Rotor droop was reduced on simulated maneuvers: up to 25 percent for a wind gust and up to 85 percent for a large collective pitch transient.

After the controls program, ceramic turbine tip shrouds were investigated for operation in a turboshaft engine. The Army/NASA Small Engine Technology program contractors came to the unanimous conclusion that the most significant impact in small engine technology could be made in the application of advanced materials, such as ceramics (ref. 10). Ceramic turbine tip shrouds have potential for increasing small gas turbine thermal efficiency by allowing higher turbine inlet temperatures and less shroud cooling air. There is also a possible reduction of component weight.

Figure 6 presents schematics of two concepts that were considered for evaluation. The configuration which was demonstrated in the STER program (ref. 11) is shown in figure 6(a). This concept incorporates a thick NiCoCrAlX bond coat onto which a yttria stabilized zirconia insulating layer was plasma sprayed. The other concept which was not ready for demonstration at the time incorporated a yttria stabilized zirconia layer sprayed onto a low density sintered metal strain isolating pad (fig. 6(b)). The engine test program was preceded by a bench test of samples to generate a level of assurance that the shrouds would survive in the engine environment. Then the engine, with the ceramic tip shrouds installed, was operated through 1001 cycles from idle to high power and back to idle, including over 50 hours of operation at steady state conditions. Data revealed that the temperature of the backside of the ceramic shrouds was substantially lower than the bill of material shrouds. Inspection of the shrouds after 1001 cycles revealed only mudflat cracks which provided a strain relief mechanism permitting the shrouds to withstand the cycling. This program was followed by a manufacturing technology program, not a part of the STER program, to transition the ceramic shrouds into an economically manufacturable application.

Upon completion of the ceramic shroud investigation, an engine proof-of-concept test of a method used to provide excess power for a short time, nondestructively, was conducted. At present, twin engine rotorcraft have their powerplants grossly oversized to allow for a 2-1/2 minute, one-engine-inoperative requirement, and also to allow for the power reduction possible due to hot-day, high-altitude takeoff requirements. The concept was to inject water into the turbine cooling air of a turboshaft engine, thereby lowering its temperature as it flashed to steam and increasing its cooling capacity (ref. 12). The idea was conceived in-house and, following feasibility studies and fundamental heat transfer analyses, special water injectors were built and rig tested to determine their flow characteristics. The injectors were installed in a specially instrumented engine which included pyrometry to measure turbine blade metal temperatures (fig. 7).

Analysis predicted the contingency power system was capable of increasing the power output about 17 percent for the required 2-1/2 minutes. Test data validated these predictions within the range of temperature increase allowable in unprotected components. Further development would be required to optimize the performance of the contingency power system; however, the system validation tests demonstrated the potential of this method for providing a significant power increase while not exceeding allowable blade metal temperatures. In addition, blade temperature data which was previously unavailable was obtained through the use of the pyrometer. These data are part of the data base for improved turbine designs.

The next STER program was performed in support of the LHX-Project Management Office (PMO). At the PMO's request, the STER facility was made available for the T800 Preliminary Flight Rating (PFR) thermal distortion tests. Rotorcraft engines may ingest hot gases, especially during flare and hover maneuvers near the ground. The hot gas ingestion results from engine exhaust being entrained in the rotor downwash and recirculated back to the engine inlet (fig. 8). Rocket and gun gases may also be ingested, depending upon their placement with respect to the engine inlet. The destabilizing effect of inlet flow distortions on gas turbine engines is depicted in figure 9.

Following the success of the T700 thermal distortion testing, the contractors involved in the T800 PFR source selection contacted the NASA/Army Propulsion Directorate STER team for consultation on the methods and results of the T700 distortion program. Subsequently, both T800 PFR competitors were offered the opportunity to perform their thermal distortion test in the STER facility. The LHTEC team accepted the offer, and their PFR T800 gas generator was installed in ECRL (fig. 10). Using the T700 experience base, the engine was subjected to the distortions as specified in the Engine System Specification, ESS. The results were subsequently reported by LHTEC in their Thermal Distortion Test Report. While not a research program, this effort was a significant achievement in that the program had an aggressive schedule, which would not tolerate slippage, and that schedule was beaten while successfully completing all the test objectives required by the ESS.

The most recent STER program addressed the system used to generate inlet temperature distortions. Maintaining the configuration used during the T800 thermal distortion program up to the engine inlet and using an inlet simulator to emulate the flow path up to the compressor inlet and into the inlet

particle separator, this program thoroughly defined, and attempted to improve, existing system capabilities. The effects of variations in parameters such as ducting length from the gaseous hydrogen burner to the engine inlet, and also in burner cup geometry (fig. 11) were investigated. An analytical effort is being undertaken to develop modeling tools which will be validated using the results of this experimental program.

FUTURE PROGRAMS

Upon completion of the gaseous hydrogen burner research program, the modified T700-GE-701 engine was reinstalled. The engine is being used to validate the operation and performance of an active shaft vibration control system (AVCS) on an engine. The AVCS was designed and developed in-house (ref. 13) and has been demonstrated on research rigs, however it has yet to perform in an actual engine environment. The system, shown schematically in figure 12 uses accelerometers, piezoelectric crystals, and a feedback circuit to sense shaft vibration and react to it with the application of a controlled voltage to, and therefore motion of, the crystals.

The next undertaking planned by the STER team will not take place in ECRL. It is the T800 inlet distortion development and official qualification testing (QT) . The test must be conducted at altitude, therefore plans are underway to perform them in one of the NASA Lewis major test rigs, Propulsion System Laboratory number 3 (PSL-3). The test objectives are to define the engine sensitivity to inlet flow distortions and to demonstrate stable operation of the engine when subjected to specified inlet total pressure, temperature, and combined distortions. The tests are again in support of the LH-PM and the program schedule is once again very aggressive, as was the case for the PFR thermal distortion testing.

After the T800 tests in PSL, the STER program will move back to ECRL. The next entry will be an investigation of the low speed stall characteristics of an axial-centrifugal turboshaft engine, the T55-L-712. The effort is already underway with an analysis of the axial compressor to determine its low speed performance. Contracted activity, coupled with the in-house analysis, will provide a data base for modeling the performance of the axial compressor in the low speed regime. A transient engine model will be developed in-house to analyze the rotating stall phenomena in a T55 from a system standpoint. By the summer of 1991, a T55 should be under test in ECRL to gather in-stall data for model validation. Present plans include a second entry of the T55 after analysis of stall relief mechanisms to validate their utility. This effort is unique in that it folds in elements from our 6.1 basic research activity and grants, our 6.2 advanced development programs, and support of the CH47 PM. The STER programs will continue to be structured in this way to the greatest extent possible in future years.

Also planned for the near future is a demonstration of the performance, operability, and system interactions of an advanced technology combustor in an engine. The PRPD presently has an advanced development (6.2) combustor program underway (ref. 14). The program will utilize a growth T800 combustor incorporating a compliant layer ceramic liner. Once the design, fabrication and rig test programs are completed, the combustor will be evaluated in the actual engine environment. The benefits of the ceramic matrix liner are summarized in figure 13.

Farther into the future, there are plans to evaluate the use of brush seals, a controlled pattern factor combustor, and a reconfigurable control algorithm. All three areas are being pursued in PRPD basic research (6.1) programs. Brush seals, illustrated in figure 14, offer great potential for reducing secondary flow leakages and are inherently self compensating. They were investigated for use in gas turbines some years ago and Rolls-Royce has recently demonstrated this application. There is not, however, a basic understanding of the dependence of seal performance on its design parameters and therefore on proper design methodology. The PRPD has undertaken a basic research program to investigate the fundamentals of the design and performance of brush seals (ref. 15). Plans are being made to incorporate brush seals into the build of one of our workhorse engines in the early 1990's as a replacement for shaft carbon seals, inner air labyrinth seals, or turbine tip shrouds.

The controlled pattern factor combustor is a spinoff of the use of convoluted walls to mix flow streams. This technology offers a method to achieve a significant combustor exit temperature pattern improvement and to reduce the length of both the compressor diffuser and the burner, providing substantial burner surface area and weight reduction.

An experimental program has demonstrated that the mixing capability of streamwise vorticity stirring (fig. 15), induced by a convoluted flow splitter, is maintained in the presence of heat release (ref. 16). The next phase of this effort is to investigate the combusting flow performance in terms of pressure drop, volumetric heat release, and combustion efficiency of selected flow reactor configurations. These experiments will indicate the viability of applying the streamwise vorticity stirring combustion principle to small gas turbine engine combustors. Assuming successful development of the technology, a streamwise vorticity stirred combustor will be designed and tested in the STER program. This program would investigate not only combustor aero-thermo performance, but also any interactions of this component with the complete engine system.

The reconfigurable control activity is also presently in the basic research arena (ref. 17). The objective of this program is to augment the pilot, making him more of a mission manager and less of a systems monitor, by taking advantage of the increased information available to the numerous computers on an advanced rotorcraft. The plan is to incorporate recent accomplishments in the areas of fault diagnosis, isolation, and accommodation, control learning/tuning, and artificial intelligence (expert systems) for control reconfiguration to accommodate engine component/sensor/actuator/control problems. The present program is attacking this problem on two fronts. A reconfigurable control featuring A/I in the loop is being designed in-house. Meanwhile, a university grant is investigating a hierarchical intelligent (learning) control, schematically shown in figure 16, for the solution of the engine control problem. Intermediate steps involving the engine manufacturers and control houses will be added as this program matures. Some years hence, as the successes of these separate efforts are merged, an intelligent engine control system will result, hopefully as part of a larger integrated intelligent rotorcraft flight/propulsion control system. The resulting intelligent engine control, having been bench tested, will be evaluated on an engine in the STER program.

SUMMARY OF RESULTS

The Small Turboshaft Engine Research program is being conducted by the Army Propulsion Directorate at the NASA Lewis Research Center. This program provides a vehicle for evaluating the application of advanced concepts to Army turboshaft engine systems and to investigate system related phenomena. Capitalizing on the resources at hand, in the form of both the NASA facilities and the Army people, with demonstrated capability in the area of full scale engine research, the program goal of developing a physical understanding of engine system dynamics and/or system interactions is being realized. Technologies such as contingency power have been brought from the conceptual stage through proof-of-concept in a complete system. The unique temperature distortion capabilities which were developed by NASA on large engines over the past 25 years, and have recently been refined for small engines in the STER program, have assisted AVSCOM in the T800 PFR phase and are also being employed in the QT program. The ceramic shroud evaluation began as an Army/NASA in-house project at the PRPD, and led into a mantech program. Similar shrouds are now being incorporated in advanced technology and growth Army engines.

Future STER entries will continue to investigate concepts and components developed both in-house and out-of-house. Emphasis will be placed on evaluations which have evolved from the 6.1 and 6.2, in-house and contracted investigations. The PMs will also be encouraged to continue making use of the STER resources. The STER personnel have established their reputations as experts in the field of engine system-related phenomena and engine evaluations. The STER facility has demonstrated its utility in both research and development programs.

The STER program offers the Army aviation community the opportunity to perform system-level investigations, and then offer the findings to the entire engine community for their consideration in next generation propulsion systems. In this way the results of the fundamental research being conducted to meet small turboshaft engine technology challenges will expeditiously find their way into that next generation of propulsion systems, keeping the U.S. at the leading edge of small gas turbine technology.

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Table I. Comparison of droop and overshoot of T700 baseline and LQR governors with Black Hawk rotor.

	Droop (-) or Overshoot (+)	
	T700 Baseline	LQR
40% - 70% beta*, uncompensated**, 0.1 sec		
- with no heat sink	-2.67%	-1.62%
- with heat sink	-3.09%	-2.31%
70% - 40% beta, uncompensated, 0.1 sec		
- with no heat sink	+2.83%	+1.64%
- with heat sink	+3.37%	+2.70%
0% - 70% beta, compensated**, 0.5 sec		
- with no heat sink	+5.10%	+0.71%/-0.74%
- with heat sink	+5.38%	-0.79%
70% - 0% beta, compensated, 0.5 sec		
- with no heat sink	-4.50%	0.60%
- with heat sink	+1.87%/-5.35%	+2.82%

* beta is collective pitch angle
** compensated or uncompensated with LDS

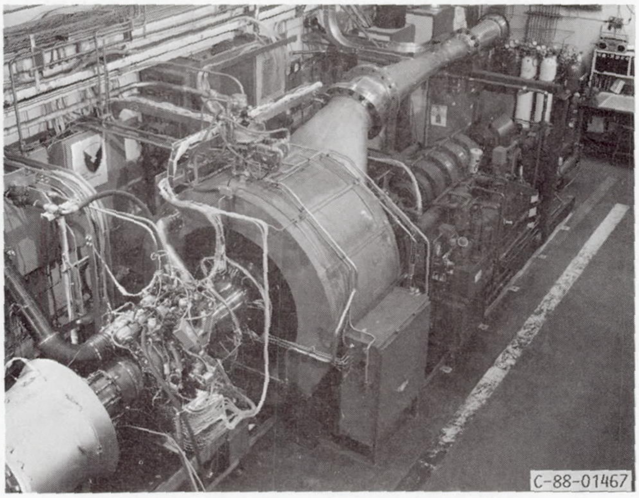


FIGURE 1. - SMALL TURBINE ENGINE RESEARCH FACILITY.

INLET-EXHAUST

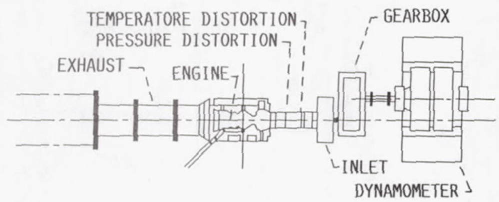
- ATM. INLET
- ATM. OR ALT. EXHAUST

DYNAMOMETER-GEARBOX

- 2,500 hp
- MOMENT OF INERTIA: 0.4-1.2 SLUG-FT ^{2}
- TIME CONSTANT < 1 SEC

TEMPERATURE DISTORTION

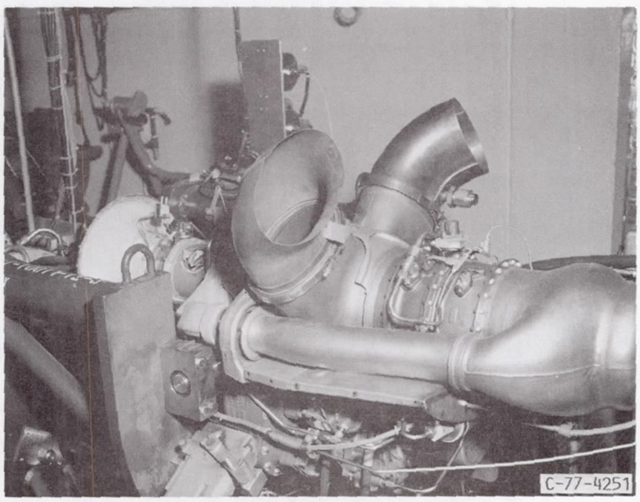
- > 300 °F RISE
- RAMP RATES > 2,000 °F/SEC
- INDIVIDUALLY CONTROLLED SECTORS



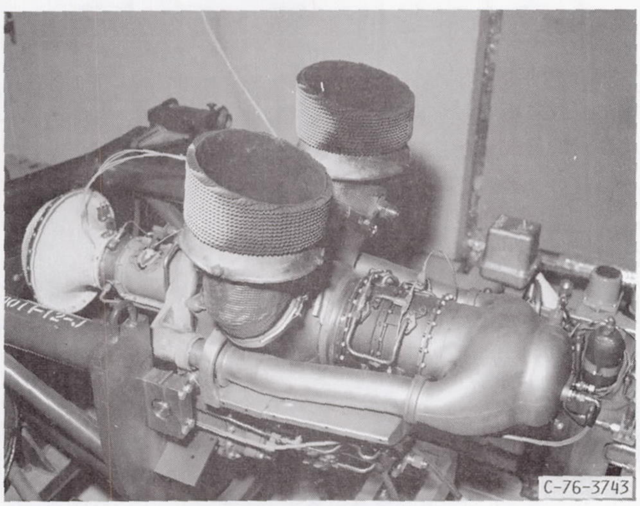
PRESSURE DISTORTION

- SCREEN PATTERNS

FIGURE 2. - STER FACILITY CAPABILITIES.



(a) WITH STANDARD EXHAUST STACKS.



(b) WITH IR SUPPRESSORS.

FIGURE 3. - T63/IR SUPPRESSOR INSTALLATION.

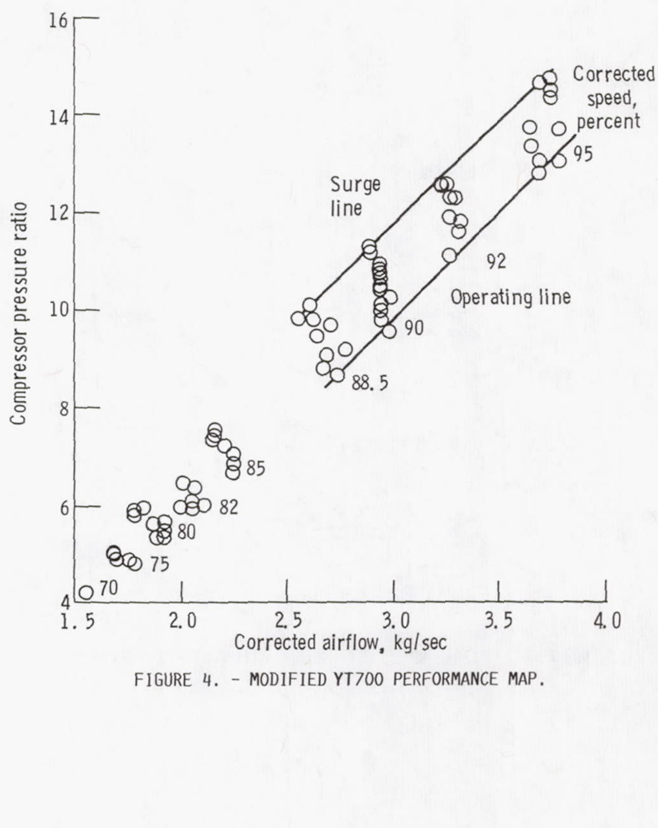


FIGURE 4. - MODIFIED YT700 PERFORMANCE MAP.

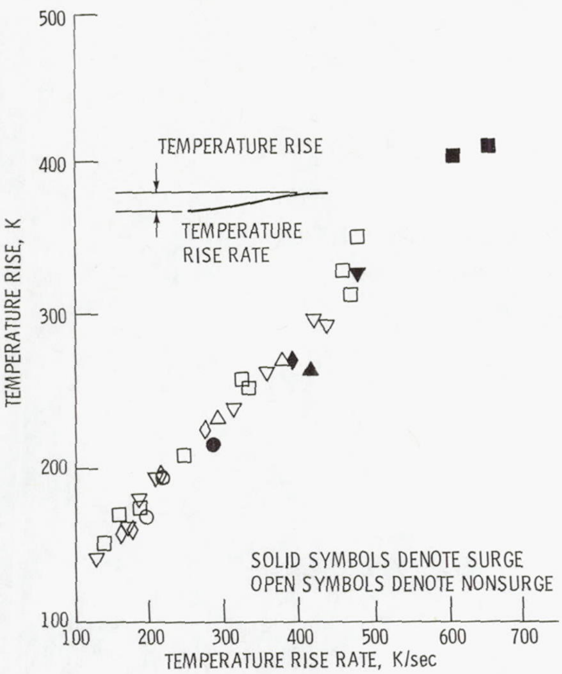
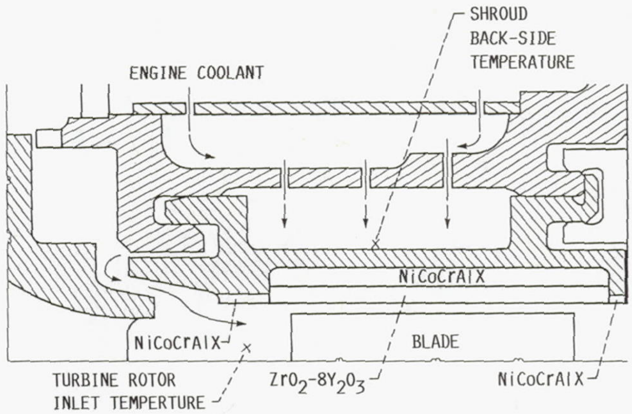
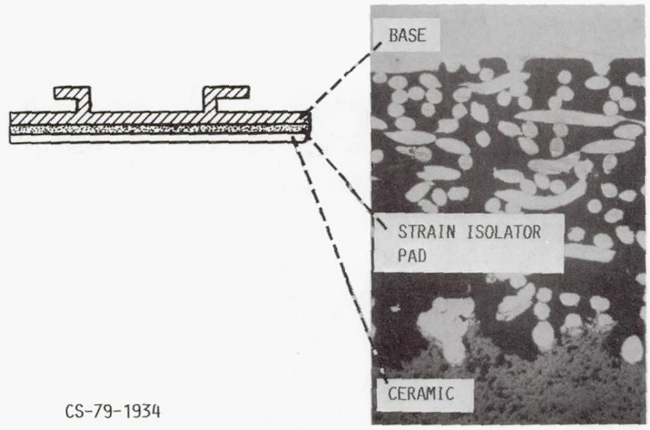


FIGURE 5. - EFFECT OF THERMAL DISTORTION RAMP ON STER ENGINE STABILITY.



(a) CERAMIC SHROUD DEMONSTRATED ON STER ENGINE.



(b) ADVANCED CERAMIC SHROUD CONCEPT.

FIGURE 6. - SCHEMATICS OF CERAMIC SHROUDS FOR SMALL TURBOSHAFT ENGINES.

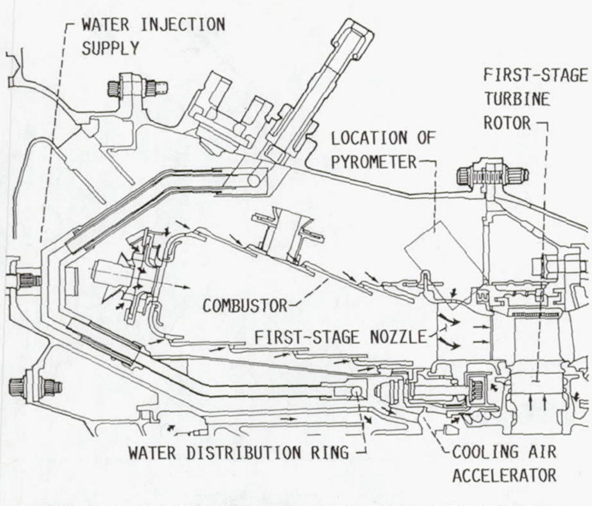


FIGURE 7. - CONTINGENCY POWER INSTALLATION WITH PYROMETRY.

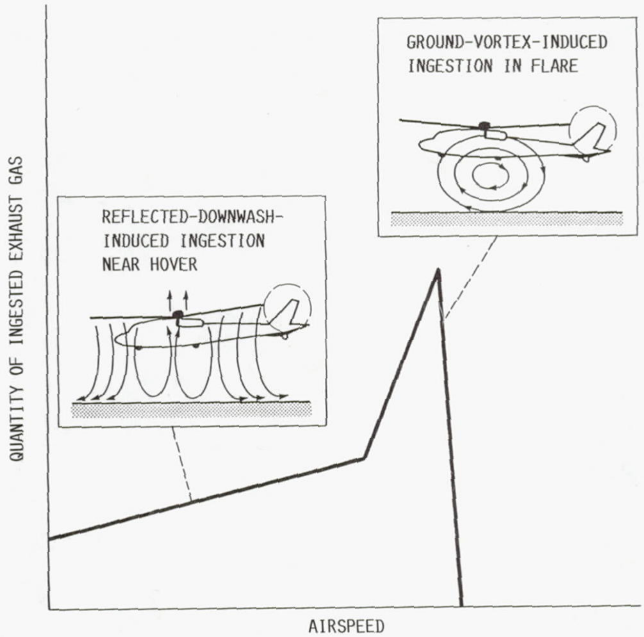


FIGURE 8. - EXHAUST GAS REINGESTION NEAR GROUND.

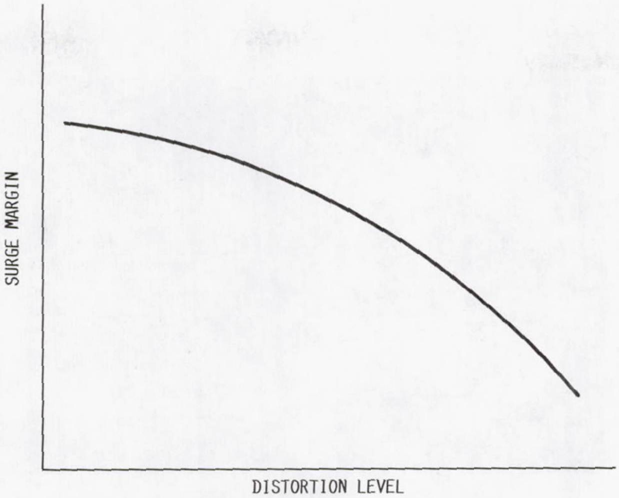


FIGURE 9. - ENGINE SENSITIVITY TO INLET FLOW DISTORTIONS.

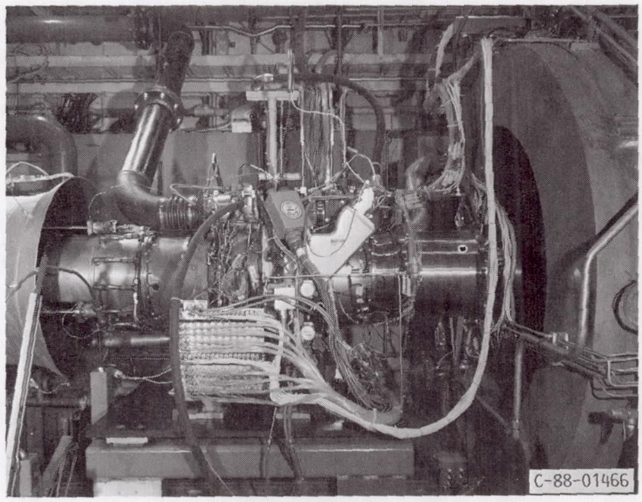
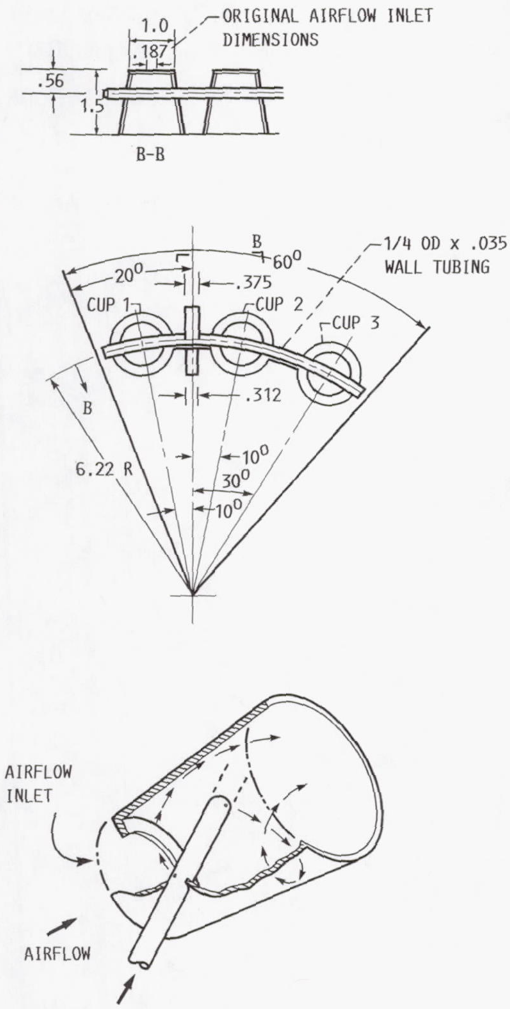


FIGURE 10. - T800-LHT-800 GAS GENERATOR INSTALLATION.



MODIFICATION NUMBER	AIRFLOW INLET
01	.25
02	.375
03	1/16 HOLES
04	1/16 HOLES
05	1/16 HOLES
06	1/16 SLOT

FIGURE 11. - HYDROGEN BURNER CUP TEST CONFIGURATIONS.

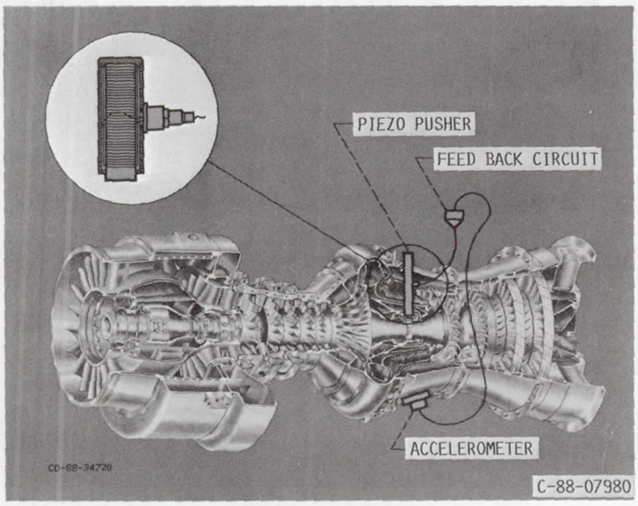


FIGURE 12. - REPRESENTATIVE AVCS INSTALLATION.

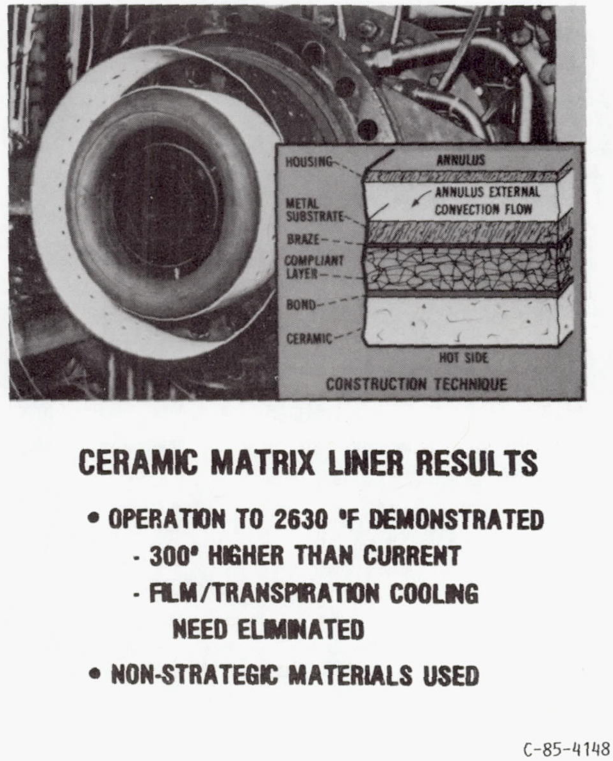


FIGURE 13. - CERAMIC MATRIX COMBUSTOR LINER.

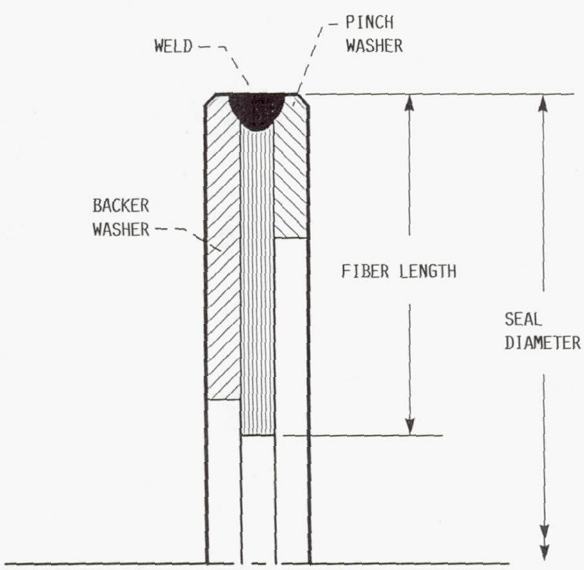


FIGURE 14. - BRUSH SEAL SCHEMATIC.

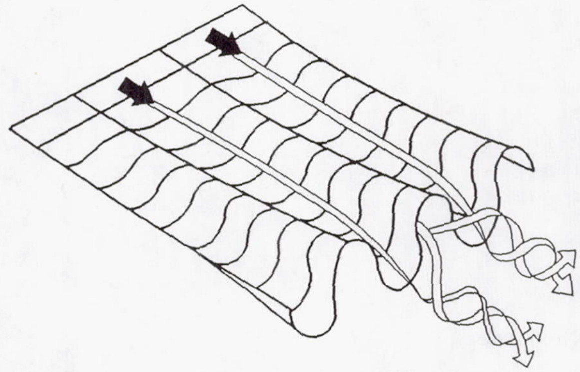


FIGURE 15. - STREAMWISE VORTICITY STIRRING CONCEPT.

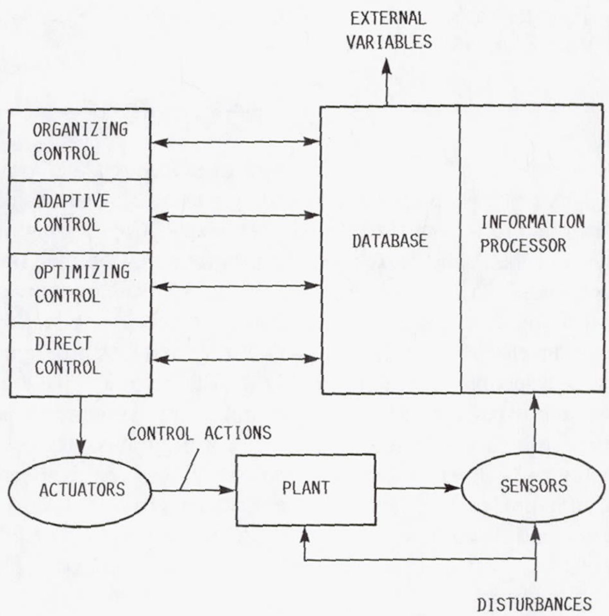


FIGURE 16. - HIERARCHICAL CONTROL ORGANIZATION.

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Report Documentation Page

1. Report No. NASA TM-103278 AVSCOM TR 90-C-021
2. Government Accession No.
3. Recipient's Catalog No.
4. Title and Subtitle
An Update of Engine System Research at the Army Propulsion Directorate
5. Report Date
6. Performing Organization Code
7. Author(s)
George A. Bobula
8. Performing Organization Report No.
E-5726
10. Work Unit No.
505-62-OK
1L162211A47A
9. Performing Organization Name and Address
NASA Lewis Research Center
Cleveland, Ohio 44135-3191
and
Propulsion Directorate
U.S. Army Aviation Systems Command
Cleveland, Ohio 44135-3191
11. Contract or Grant No.
13. Type of Report and Period Covered
Technical Memorandum
12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546-0001
and
U.S. Army Aviation Systems Command
St. Louis, Mo. 63120-1798
14. Sponsoring Agency Code
15. Supplementary Notes
Prepared for the Rotary Wing Propulsion Specialists' Meeting sponsored by the American Helicopter Society, Inc., Williamsburg, Virginia, November 13-15, 1990.
16. Abstract
The Small Turboshaft Engine Research (STER) program is being conducted by the Army Propulsion Directorate at the NASA Lewis Research Center. This program provides a vehicle for evaluating the application of emerging technologies to Army turboshaft engine systems and to investigate related phenomena. Capitalizing on the resources at hand, in the form of both the NASA facilities and the Army personnel, the program goal of developing a physical understanding of engine system dynamics and/or system interactions is being realized. STER entries investigate concepts and components developed both in-house and out-of-house. Emphasis is placed upon evaluations which have evolved from on-going basic research (6.1) and advanced development (6.2) programs. Army aviation program managers are also encouraged to make use of STER resources, both people and facilities. The STER personnel have established their reputations as experts in the fields of engine system experimental evaluations and engine system related phenomena. The STER facility has demonstrated its utility in both research and development programs. The STER program provides the Army aviation community the opportunity to perform system level investigations, and then to offer the findings to the entire engine community for their consideration in next generation propulsion systems. In this way results of the fundamental research being conducted to meet small turboshaft engine technology challenges expeditiously find their way into that next generation of propulsion systems.
17. Key Words (Suggested by Author(s))
Small gas turbine
Turboshaft
Turboshaft testing
Engine research engine systems
18. Distribution Statement
Unclassified – Unlimited
Subject Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	16	A03

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161